SINGLE BUBBLE INITIATION TECHNIQUE
BY
A LASER BEAM

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ABSTRACT

A technique to initiate a single bubble is developed by shooting a laser beam, either on a tiny spherical thermocouple of approximately .012" diameter or on a thin metallic sheet of approximately .002" thickness. The thermocouple is immersed in a pool of boiling water at various sub-cooled temperature, the thin metallic sheet is a part of the bottom side of the water container. The temperature history of the spherical thermo-couple is obtained for different subcooled water temperatures. Pictures at 25,000 frames per second for the initial bubble growth are also obtained.

A bubble can be initiated around the thermocouple under various subcooled water temperatures even as high as $40^{o}C$. During the initial growth period the sphericity of the bubble is quite good and consistent with other data.

The initial growth rate of the bubble for the duration of the first 300 micro seconds seems to agree consistently from the classical predictions. It is proportional to the square root of the time.

INTRODUCTION

Most experimental investigations [1,2,3,4] in nucleate boiling are based on the study of high speed photographs of many bubbles generated in a pool of saturated or subcooled liquids. Usually one particular bubble out of hundreds is chosen to be analyzed, the growth rate during and after the initial growth shape may be correlated with some important parameters, such as surface tension, viscosity, inertia, the surface condition of the heating surface, etc. Heat transfer may also be evaluated under various conditions.

Most analytical results [5,6,7,8] are considering the bubble to be perfectly spherical, then the Rayleigh or extended Rayleigh equation is to be solved to give the dynamics of the bubble growth in terms of various parameters such as surface tnesion, viscosity, and inertia, etc. Heat balance equations may also be written for the bubble to evaluate the rate of heat transfer.

Ultimately the analytical and experimental results are to be correlated such that the basic important parameters can be tied into the boiling heat transfer and the bubble growth dynamics into deduced usable forms for practical applications.

The assumption of the sphericity of the generated bubbles in conventional boiling, namely, the bubbles generated from the heated flat surface, is not at all very good, especially during the initial growth phase of the bubble, this is due to the characteristics of the heating surface. Furthermore, the single bubble chosen to be analyzed as in the experimental results does not represent a single bubble in an undisturbed large medium of the liquid. The hydrodynamics of one bubble is certainly influenced by the presence of many other bubbles generated before it as in the case of the conventional boiling.

APPROACH OF THIS STUDY

It is the intention of this study to generate a single spherical bubble by the use of a laser beam in an undisturbed liquid medium where the hydrodynamic influence of other bubbles is absent. Experimental observations of the bubble growth, particularly the initial growth phase, may be obtained by different subcooled conditions, energy inputs and eventually various liquids, through high speed photography of single bubble growth. If the sphericity of the growing bubble is good, the observed experimental growth rate may be compared to the analytical results which are based on the analysis of a spherical single bubble with no consideration of hydrodynamic influence of other bubbles.

In order to maintain a spherical geometry, a spherical thermocouple of approximately .012" diameter was formed by welding two .003" iron-constantan wires together. The thermocouple leads were connected to the oscilloscope such that the milivoltage output versus time can be traced after the laser beam hit the junction, thus the temperature history of the thermocouple is recorded. The motive of this instrumentation is to provide a means of measuring the heating surface temperature in addition to the spherical geometry. The rate of heat transfer to the bubble, hopefully, may be evaluated quantitatively. A second thermocouple was installed about .025" distance apart from the first one which was hit by the laser beam, (the thermocouple leads are also connected to the oscilloscope) this provides a means of measuring the temperature in the neighborhood of the interface between the vapor and the liquid. Hopefully, the thermal boundary layer thickness around the interface may be evaluated.

A single bubble was initiated on a thin flat metal plate which was a central part of the bottom plate of the liquid container by the use of a laser beam hitting the thin plate from underneath. A thermocouple was installed about a distance of .030" above the thin plate in the hope of measuring the temperature of the vapor in the bubble and also the temperature in the neighborhood of the interface of the vapor and the liquid.

Although some quantitative measurements have been made, these only represent a rather qualitative picture of all experiments and serve as more or less a prelude of future research. The emphasis right now is to see the feasibility of the initiation technique of a single bubble, preferably spherical, by the use of a laser beam. Ultimately in the future, quantitative analysis are to be considered for many different conditions.

INSTRUMENTATION AND EQUIPMENT

A boiler chamber consisting of a one-half-inch thick aluminum bottom plate containing a heating element and six-inch square glass sides was constructed for purposes of this study. A raised center section provides for the installation of special thermocouple fixtures. A laser microposition was designed and fabricated to be attached to the underside of the chamber to permit accurately positioning the laser with respect to the thermocouples. The set-up is shown in Figure 1.

The laser is a Hughes model 200 ruby with an output energy of about one joule at a wavelength of 6943 angstroms. The output energy can be varied by varying the firing voltage. At 1350 volts the output is maximum at about one joule. The threshold voltage, where the laser just operates, is at about 900 volts at room temperature. The output varies from zero to one joule as the excitation voltage is changed from 900 to 1350 volts. The laser output is quite sensitive to ambient temperature, and slight variations in output from shot to shot are not uncommon. It appears that it would be advantageous to provide temperature control and power monitoring

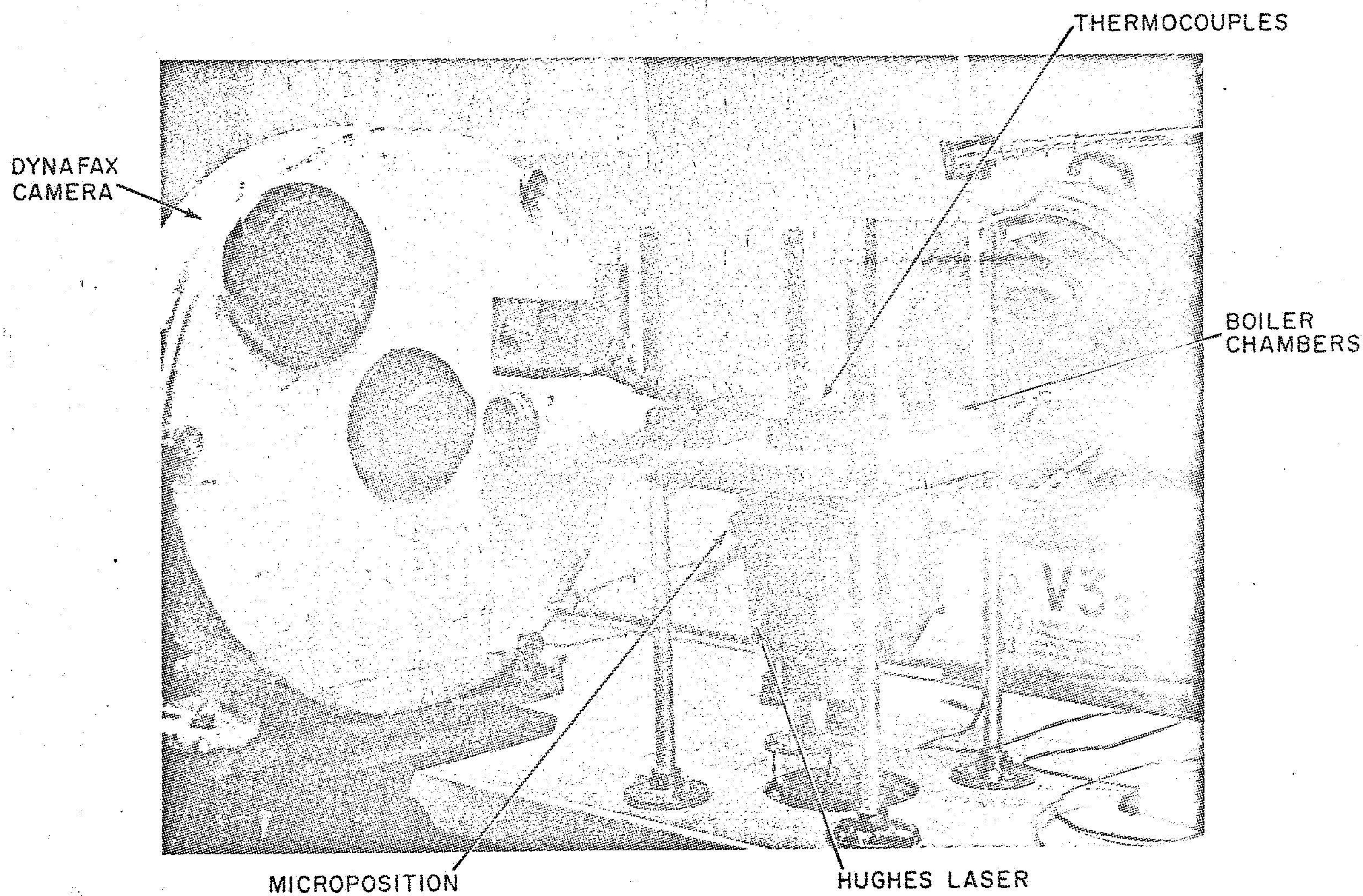


Figure 1. Equipment Set-up

facilities for future work.

The thermocouple output voltage was amplified by a set of six Kintel D. C. amplifiers and recorded photographically with a Tektronix type 547 oscilloscope equipped with a polaroid oscilloscope camera. The input to the oscilloscope was filtered with a single stage R-C filter to eliminate frequencies higher than about 5000 cycles. The oscilloscope was triggered at the same time the laser was fired by means of a trigger pulse derived from the laser control system. The oscilloscope and amplifiers are shown in Figure 2.

A Beckman & Whitley Dynafax camera was used to photograph the bubble growth. The camera was operated at 25,000 frames per second with an exposure time of 1.25 microseconds per frame. Illumination was provided by means of a xenon flash tube mounted in a parabolic reflector. The flash tube was placed behind the chamber to back light the bubble. A shadowgraph is then obtained with sharp edges which can be accurately measured to determine growth rate. The camera-chamber setup is also shown in Figure 1. A view of the entire control system is shown in Figure 3.

Test photos indicated that the flash lamp exposes 5 frames prior to initiation of the laser. The laser beam is then on for about 20 frames when operated at peak power. Most of the energy is delivered within the first 8 or 10 frames. Thus it may be assumed that the oscilloscope trace starts between the fifth and sixth frame of the dynafax record. Test shots made to determine laser operating time were on Eastman #2475 film. Test runs were made on Tri-X film, which is insensitive to the laser light.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental Conditions

A number of experimental runs were made under various conditions to determine the feasibility of using the laser system described previously for initiating

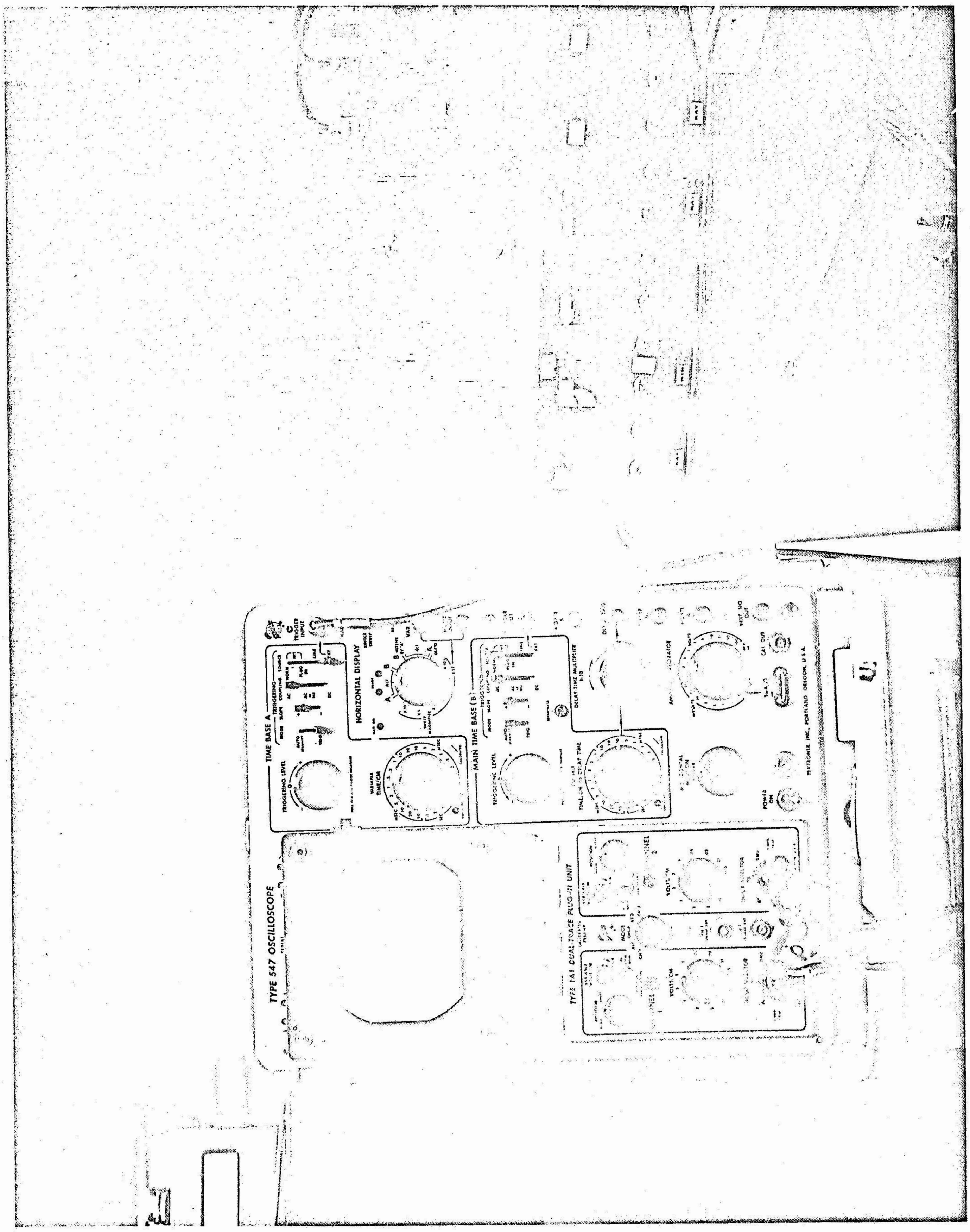


Figure 2. Oscilloscope and Amplifiers

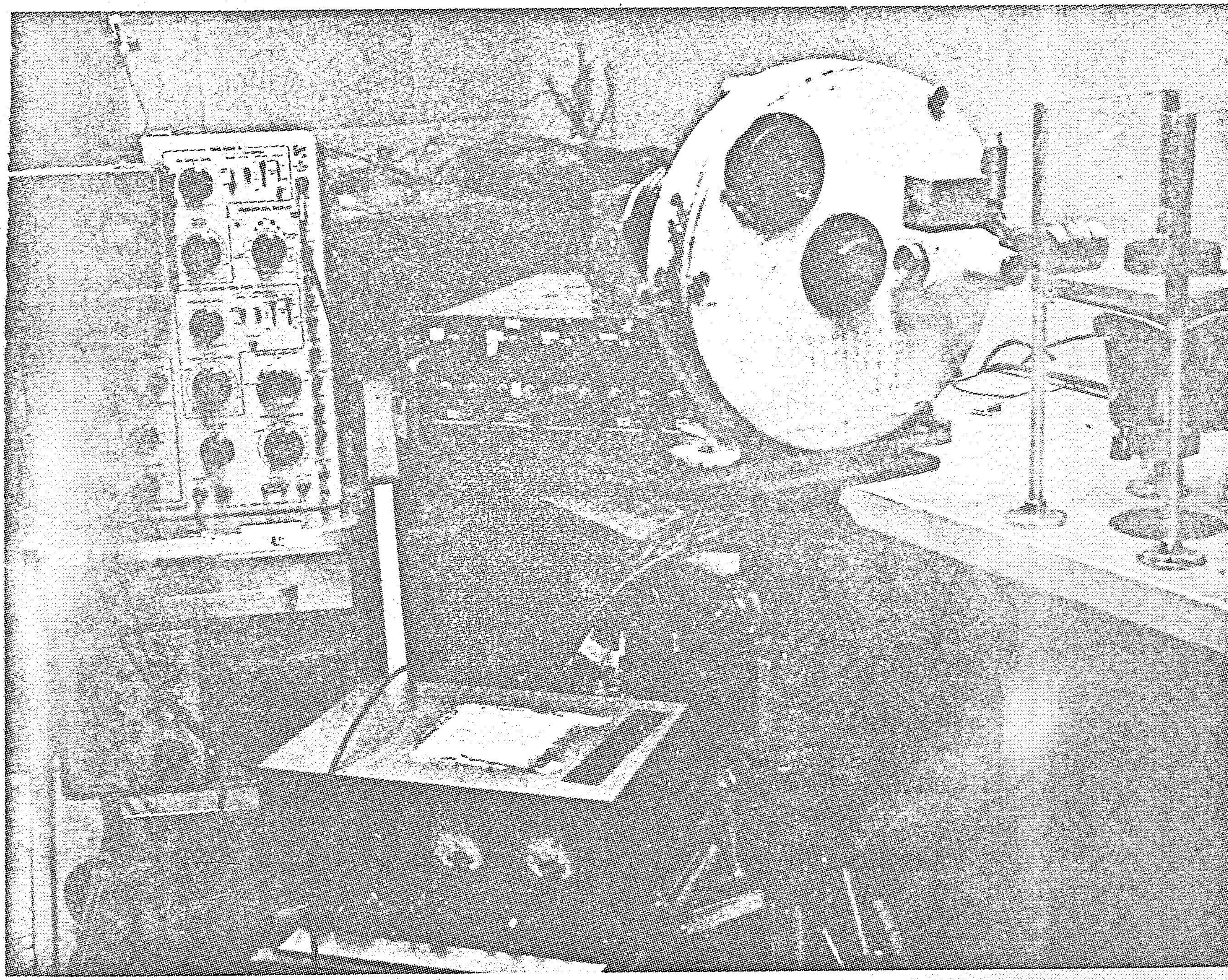


Figure 3. The Entire Control System

a single bubble. The experiments were performed under conditions as stated in the approach of the study all in subcooled water. Various conditions for a number of experimental runs are listed in Table I.

TABLE I. Conditions for Experimental Runs

Run No.	7	8	9	10	11	2A	3A	4A	5A	1B	1B
Laser Voltage	1200	1200	1200	1200	1200	1050	1100	1150	1200	1350	1200
Water Temperature	94	90	85	80	70	94	94	94	94	94	94
T. C., ^{o}F	565	225	225	225	T.C. Broken						

Typical bubble growth pictures of the first 12 frames are shown in Figure 4 through 6. The 12 frames represent the initial growth phase in a time period of 480 microseconds duration.

Figure 4 shows that a single bubble grew around a thermocouple junction after hit by the laser beam. The temperature of the water bath was kept at 94^{o}C and the laser voltage was 1150. The picture represents the experimental run 4A. The sequence of the bubble growth clearly shows that the bubble is quite spherical in shape except for the first two frames where one side of the bubble is somewhat out of shape. The bubble keeps growing at a rather slow pace after the 12th frame. After the 22nd frame the bubble begins to be oblong in shape and stays at about the same size after the 34th frame.

Corresponding to the conditions set forth for Figure 4, or the experimental run 4A. Figure 7 shows the poloroid picture of the temperature trace of the thermocouple hit by the laser beam and the temperature trace of the second thermocouple about .025-inch distance apart from the first one. The peak temperature of the first thermocouple is about 565^{o}F with 5 mv.

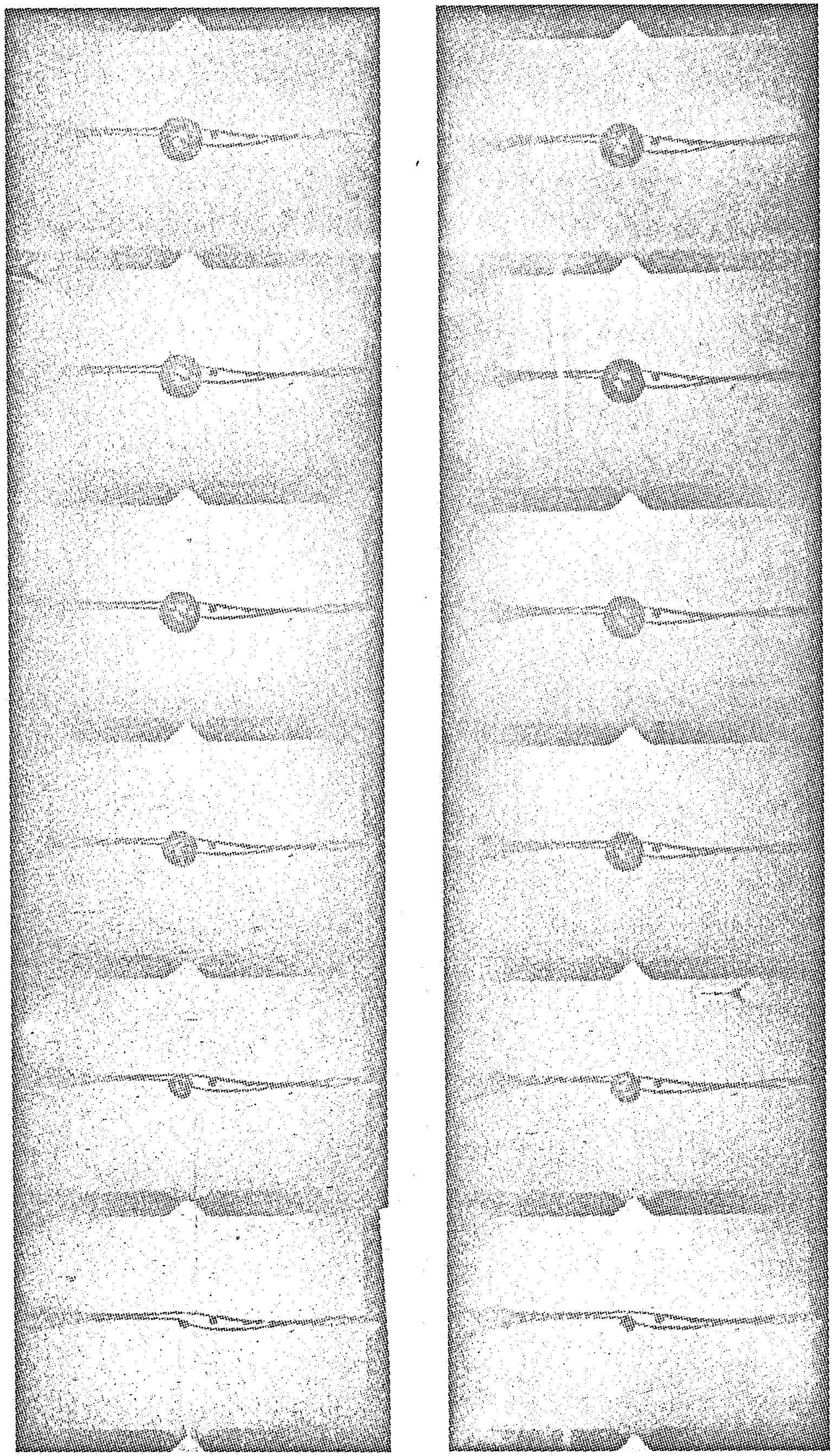


Figure 4. A Single Bubble Around a Thermocouple Junction in Water at 94° C.

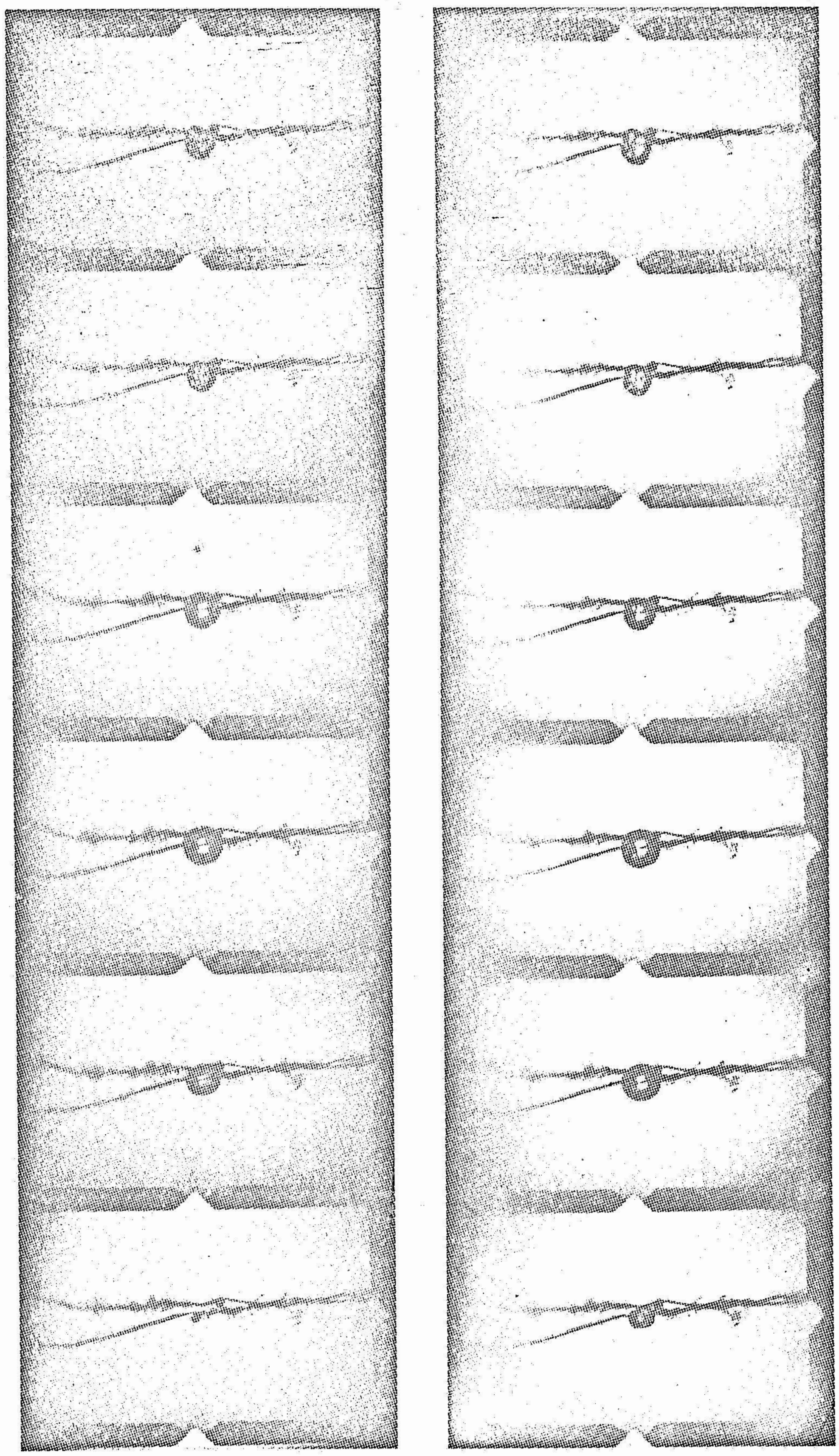


Figure 5. A Single Bubble Around a Thermocouple Junction in Water at 80° C.

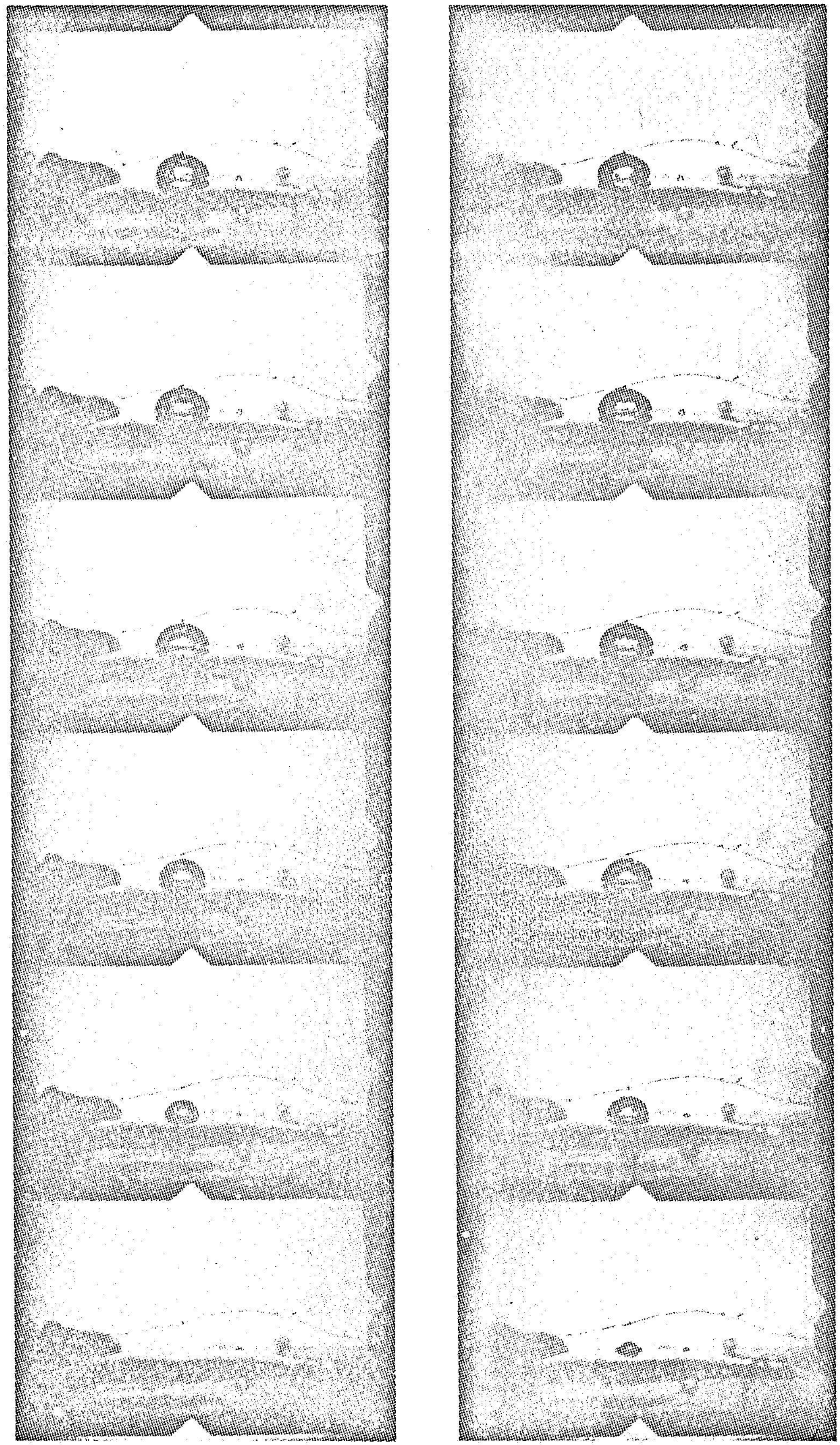


Figure 6. A Single Bubble on a Thin Flat Plate in Water at 94° F.

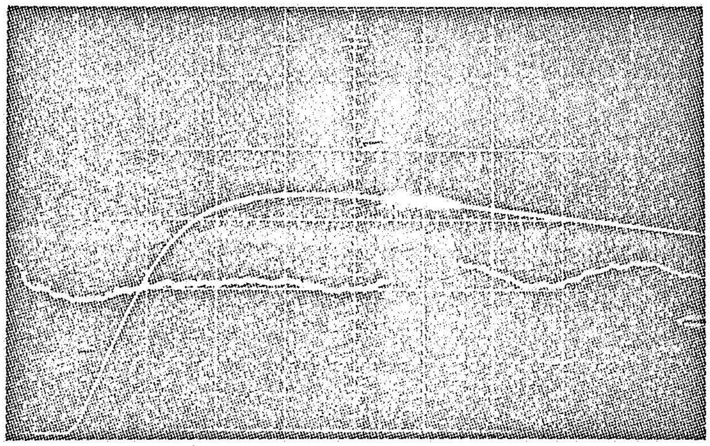


Figure 7. Thermocouple Temperature Trace Corresponding to Figure 4.

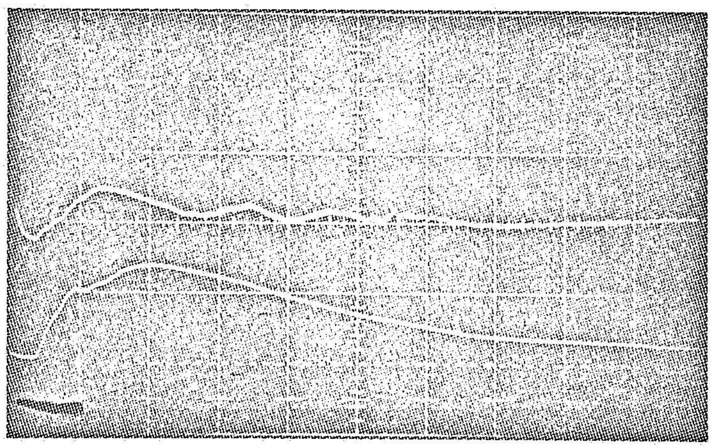


Figure 8. Thermocouple Temperature Trace Corresponding to Figure 5.

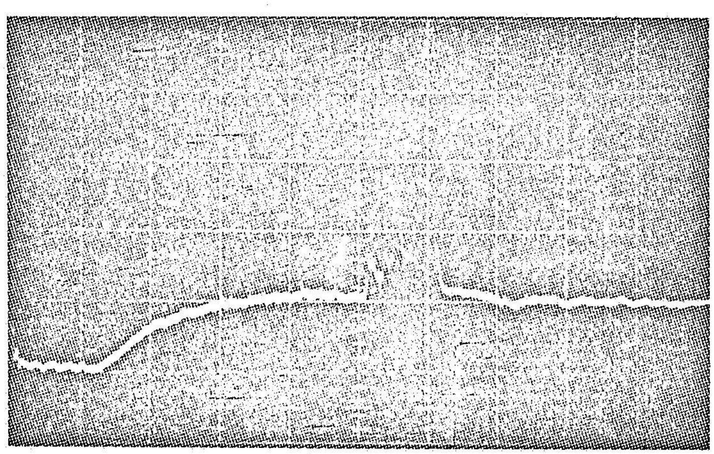


Figure 9. Thermocouple Temperature Trace Corresponding to Figure 6.

per cm. scale. This should represent the surface temperature of the thermocouple. The temperature rise from the water temperature to about 80 percent of the peak value takes about one millisecond, the time scale for the abscissa being .5 milliseconds per cm. This may be considered as the time delay due to conduction through the junction. For a very crude calculation the time lap seems to be in the right order. After the peak value the temperature does not seem to drop rapidly. This may show that the vapor in the bubble is a poor thermal conductor. In the future, the heat transfer problem of the vapor may be analyzed to correlate with the experimental measured temperature history.

Figure 5 shows the initial growth sequence of a single bubble around a thermocouple junction after being hit by the laser beam under the conditions of experimental run 10. The temperature of the water was kept at 80°C, and the laser voltage was maintained at 1200 volts. The bubble grows at a rather fast pace during the first few frames, but it begins to shrink after the 4th frame and becomes ablong in shape after about the 10th frame. After about the 16th frame the bubble begins to be unstable. This shows that the higher degree of subcooling tends to collapse the bubble as it should, although the state of the collapsing the bubble was not obtained due to the high speed chosen. The temperature trace of the second thermocouple does not shows any changes, this is due to the distance between the two thermocouples is larger than .025-inch so that the bubble did not reach the second thermocouple.

Corresponding to the conditions set forth for Figure 5, the temperature trace of the first thermocouple junction was obtained as shown in the polaroid picture of Figure 8. The trend of the temperature rise of the first thermocouple is about similar to that for Figure 7. The peak temperature is about 225°F with 5 mv. per cm. scale.(The time scale is 1 millisecond per cm for the abscissa.) The temperature trace for the second thermocouple shows a rise of peak value in the order of about .4 millivolts, which corresponds to a temperature rise of about 15°F with a scale of .5 mv. per cm. Up to this moment, not enough data are taken to give any quantitative analysis of the thermal boundary layer thickness around the interface between the vapor and the liquid. In the future, hopefully, this information may be obtained experimentally. According to the literature, this boundary layer thickness is of the order of .006 inches.

Figure 6 shows that a single bubble was initiated on a flat thin metal plate corresponding to the conditions of experimental run 1B in a water pool of 94°C, the laser voltage was 1350 volt. The non-sphericity of the bubble during its initial growth period is not as bad, although from about the 10th frame there exists contact angle between the bubble and the metal surface, thus the bubble deviates from the spherical shape. As the bubble grows larger, up to about the 18th frame, the bubble tends to be crown shaped rather than the spherical. The top part of the bubble still maintains a good spherical shape. The bubble shape seems to be similar to those bubbles produced by the conventional boiling process.

Figure 9 shows a polariod picture of the temperature obtained from the chromel-constantan thermocouple junction of about .004 inches in diameter with .001-inch diameter lead wires, placed about .030 inches above the plate. The peak temperature shows about a 19°F temperature rise with a scale of 0.2 mv. per cm. and a time scale of 1 millisecond in abscissa. The temperature seems to stay at a constant level, presumably the vapor temperature.

BUBBLE GROWTH RATE

The radius of the bubble was measured through an enlarger on a frame by frame basis. These are plotted in Figures 10 through 14.

Figure 10 represents the initial growth of the bubble around a thermocouple junction for experimental runs 2A, 3A, 4A and 5A. The initial growth rate of the bubble is faster for a higher laser voltage or laser energy, the results give a consistent trend.

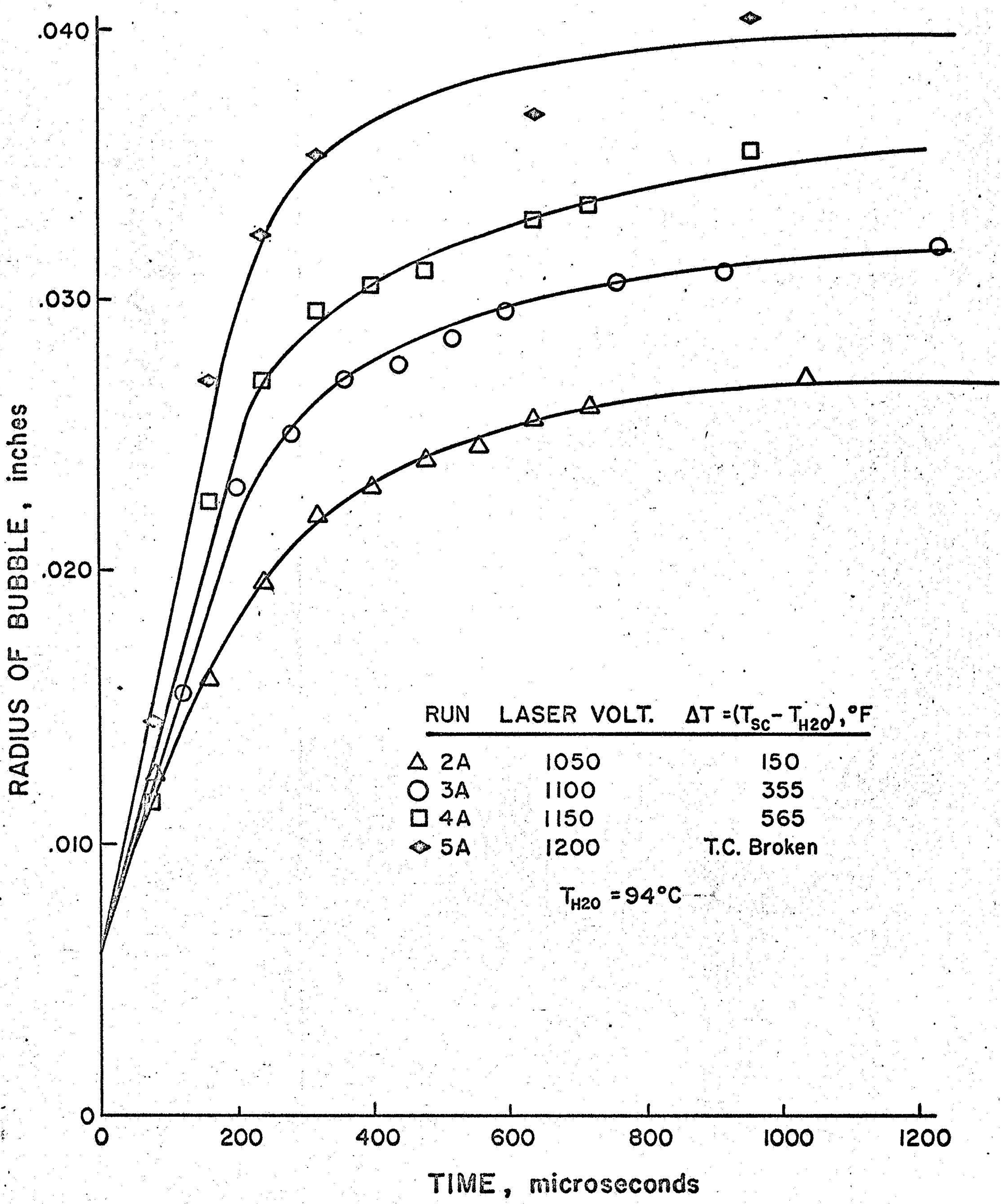
Figure 11 shows the initial growth of the bubble from a flat plate for experimental runs 1B and 3B at two different energy inputs. It is also consistent to see that the bubble grows faster in the initial phase for a higher energy input.

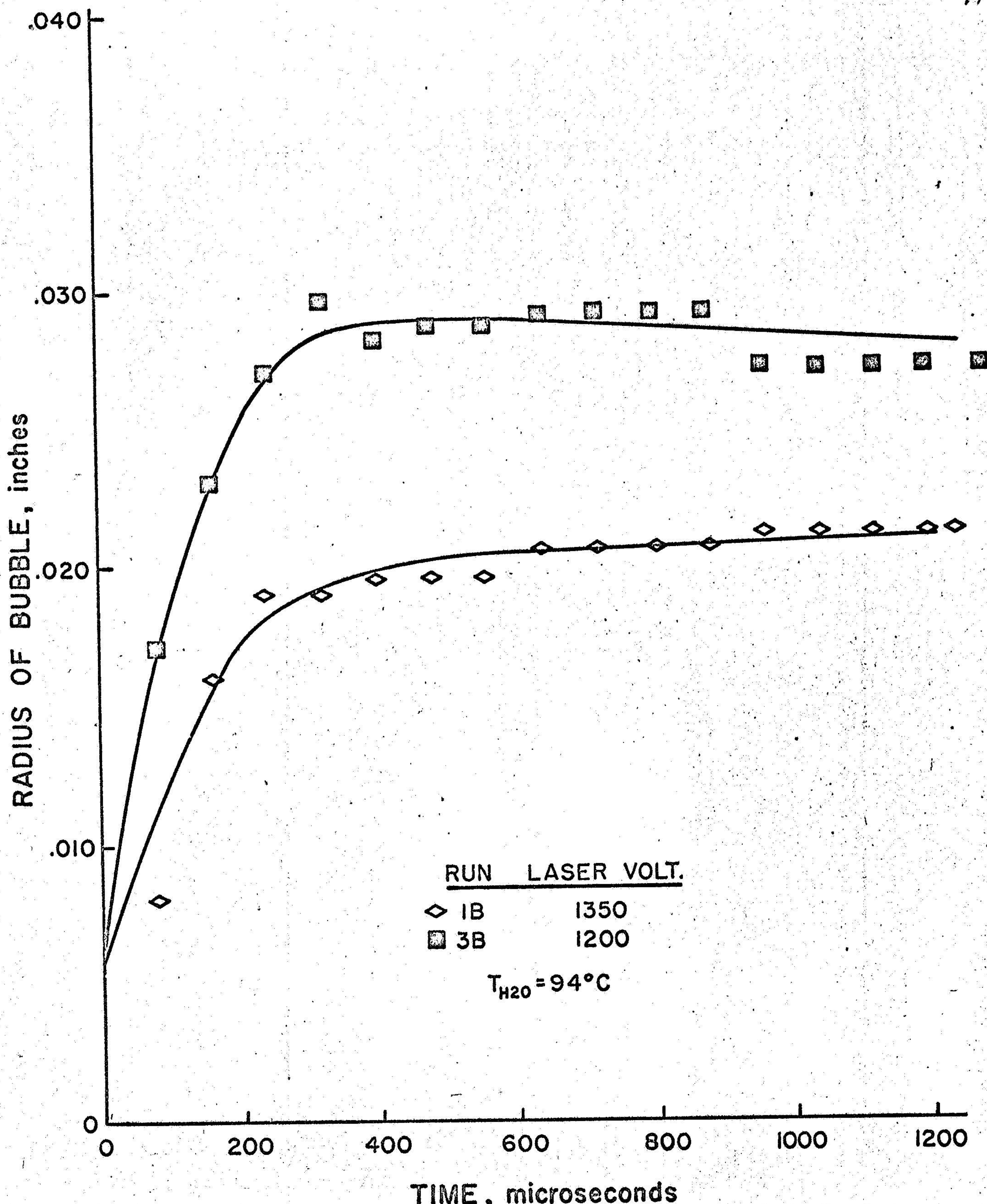
Figure 12 shows that initial growth within the first 320 microseconds of the experimental runs 2A, 3A, 4A, 5A, 1B and 3B plotted against the square root of time. It is interesting to see that most of the results follow a straight line relation as predicted in the literature.

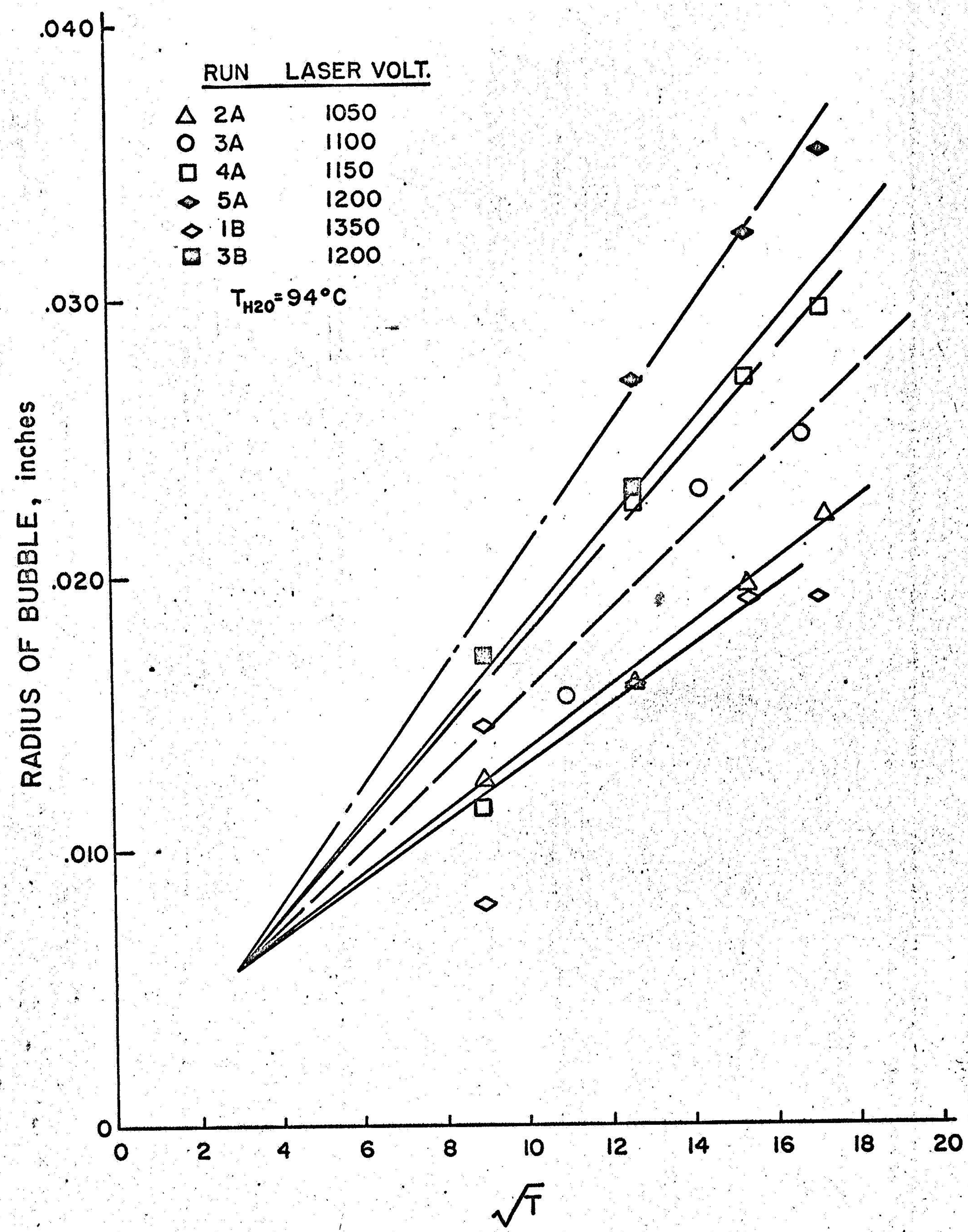
Figure 13 represents the initial growth of a single bubble around a thermocouple junction for the experimental runs 7, 8, 9, 10 and 11 at various subcooled temperatures. After about 200 microseconds it is obvious that the bubble grows less for a higher subcooled temperature or lower water temperature.

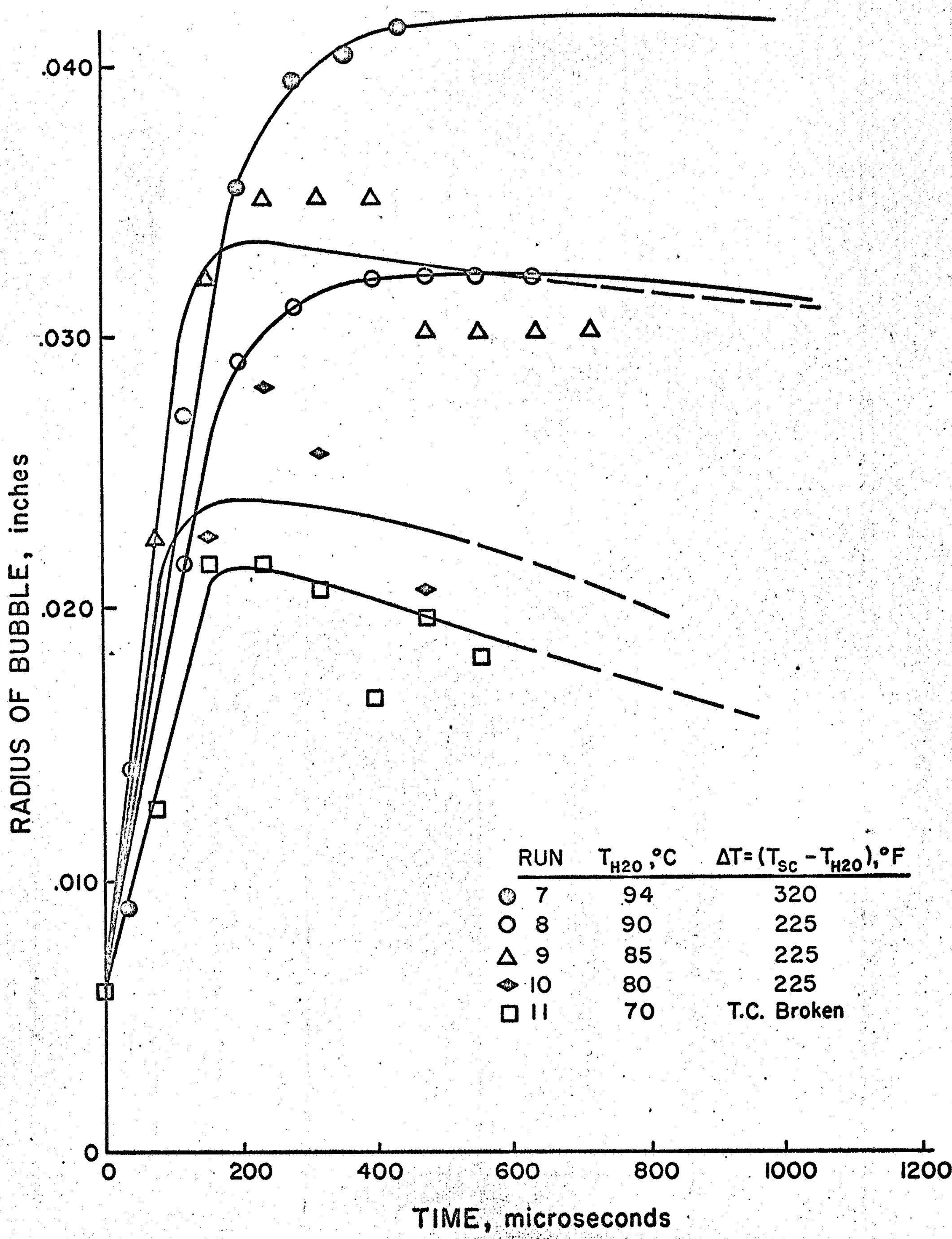
Figure 14 shows that the initial growth rate plotted against the square root of time also follows a linear relation fairly well.

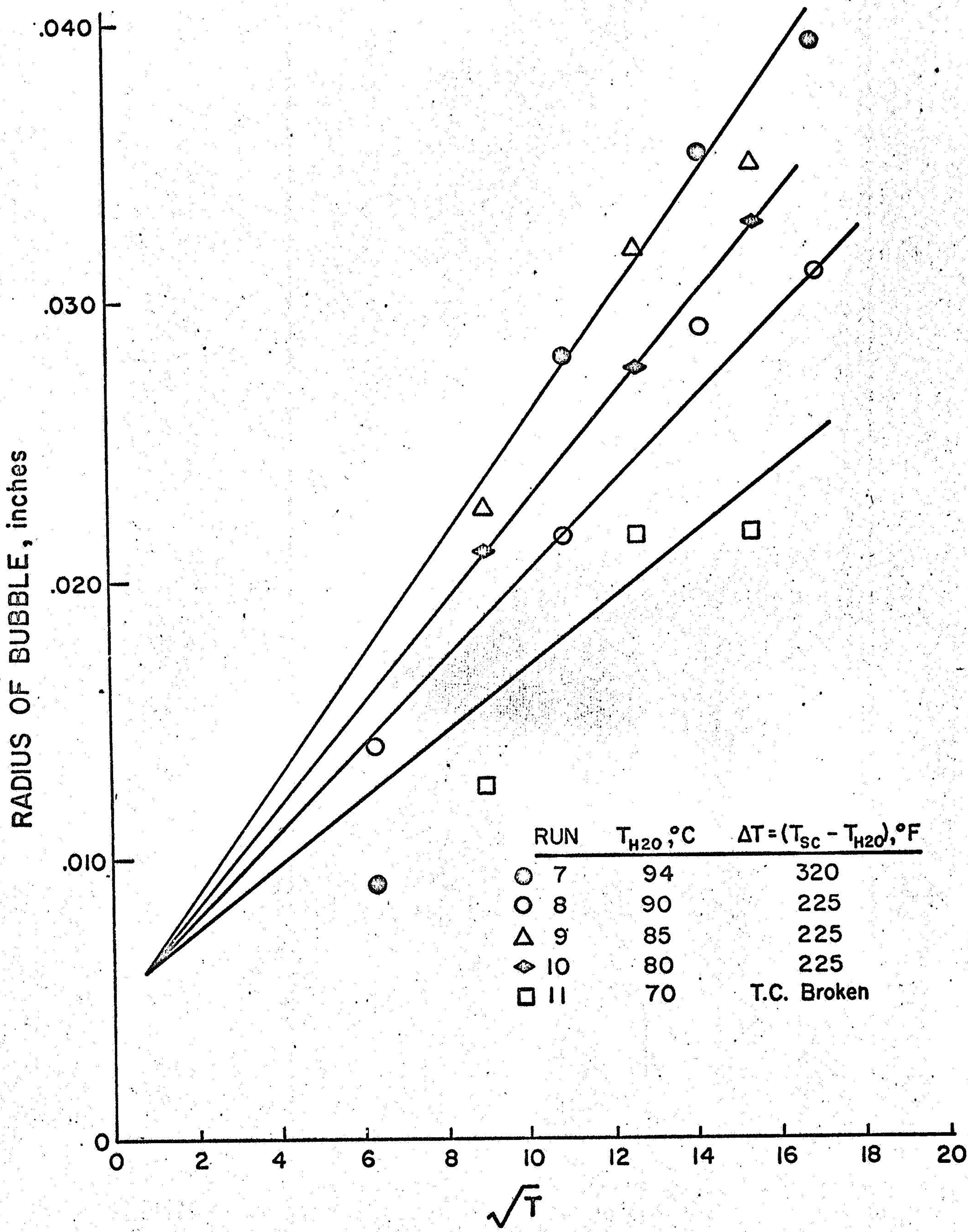
In general, the experimental results are quite consistent in trends. They do give reasonable qualitative results as well as partial quantitative


.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0
200
400
600
800
1000
1200
TIME, microseconds
RUN LASER VOLT. ΔT =(T_SC – T_H2O), °F
2A 1050 150
3A 1100 355
4A 1150 565
5A 1200 T.C. Broken
T_H2O = 94°C


.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0
200
400
600
800
1000
1200
TIME, microseconds
RUN LASER VOLT.
IB 1350
3B 1200
T_{H2O} = 94°C


RUN LASER VOLT.
2A 1050
3A 1100
4A 1150
5A 1200
1B 1350
3B 1200
T_{H2O}=94°C
RADIUS OF BUBBLE, inches
.040
.030
.020
.010
0
0 2 4 6 8 10 12 14 16 18 20
$\sqrt{T}$


.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0
200
400
600
800
1000
1200
TIME, microseconds
RUN
T_{H2O}, °C
$\Delta T = (T_{SC} - T_{H2O})$, °F
7 94 320
8 90 225
9 85 225
10 80 225
11 70 T.C. Broken


.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0 2 4 6 8 10 12 14 16 18 20
√T
RUN
T_{H20}, °C
$\Delta T = (T_{SC} - T_{H20})$, °F
7 94 320
8 90 225
9 85 225
10 80 225
11 70 T.C. Broken

results. As more sophisticated instrumentation is developed in the future, a much more quantitative analysis will give better answers to the basic problem of bubble dynamics and boiling heat transfer.

CONCLUSIONS

In conclusion, the initiation of a single bubble by the use of a laser beam is feasible. The spericity of a single bubble is reasonably good. The growth rate during the initial stage of the bubble growth in the order of 300 microseconds seems to follow a linear relation with the square root of time as predicted in the literature, although at this stage of the study the instrumentation may not be sophisticated to give a precise quantitative result.

FUTURE STUDY

In the future, the techniques of temperature measurements are to be improved, more experiments are to be conducted to obtain good reproducible runs under various conditions, particularly various liquids of different viscosity and surface tension are to be considered such that the effect of the surface tension and viscosity may be singled out. In the mean time the analytical solution of bubble dynamics and heat transfer, including viscosity, may be obtained. The correlation between experimental runs and analytical solutions are to be considered.

ACKNOWLEDGEMENT

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